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Evidence at the 10^{-18} probability level against the production of magnetic monopoles in proton interactions at 300 GeV/c*

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An electromagnetic search for magnetic monopoles that requires very few assumptions about their properties has been performed in material exposed to protons accelerated at Fermilab, to electrons at SLAC, and to pp interactions at the CERN ISR. The most significant irradiation (Fermilab, 300 GeV/c) produced 2.5×10^{18} primary proton-aluminum interactions. No monopoles were found. If monopoles exist with masses less than 12 GeV, the probability of pair production in a proton-nucleon collision is of the order of 10^{-18} or less with 95% confidence.

INTRODUCTION

Since 1931,[1] the existence of magnetic monopoles has been repeatedly invoked in theories[2] in connection with the observed phenomenon of electric charge quantization.[3] However, increasingly exhaustive experiments designed to find and isolate magnetic charges have all had negative results.[4-10] These experiments would have detected monopoles with various magnetic charges, masses, production cross sections, and specific binding properties to matter.[11] In this paper a very general search for monopoles that can be produced at present accelerators is reported. It uses a modified version of the detector[12,13] used in a previous cosmic-ray search.[6,8] It covers a vast domain of charges and masses, requires no extraction of monopoles from material, and, to be valid, needs very few assumptions about the properties of monopoles.

IRRADIATION AND SAMPLE PREPARATION

In an experiment at the Fermi National Accelerator Laboratory (Fermilab), aluminum targets were irradiated by about 4×10^{18} protons accelerated to several hundreds of GeV in the hope of producing and trapping monopole pairs. The target specifications are given in Table I. From the accelerator records and the geometry of the targets, the number of proton interactions is computed at each energy. Within 30%, it agrees with the estimation based on the ^{22}Na and ^{7}Be radioactivity in the first centimeter of targets 1, 2, and 3. The total for all targets is shown in Table II.

In order to search for monopoles that could have been produced in pairs in some of these interactions and trapped in the targets, the target material was first ground into thin chips to separate the north and south poles of a pair, using

TABLE I. Characteristics of the aluminum targets exposed to the Fermilab beams.

Target no.	Length (cm)	Location of irradiation[a]	No. of protons in the beam	No. of interaction lengths before the target
1	30	ν	1.3×10^{18}	0
2	30	ν	1.3×10^{18}	0
3	45	ν	1.0×10^{18}	0
4	16.5	ν	0.2×10^{18}	0.3
5	41	p[b]	0.4×10^{18}	0.5

[a] ν stands for neutrino lab.
[b] p stands for proton lab, eastern section.

TABLE II. Energy distribution of the exposures of the material analyzed. R_{max} is the maximum ratio of monopole pairs to primary interactions (95% confidence).

Origin	Beam energy (GeV)	Material	No. of primary interactions	R_{max}	Maximum monopole mass (GeV)	Range of ν [a]
Fermilab	200	aluminum	2.0×10^{17}	1.6×10^{-17}	8.8	1 to 7
Fermilab	300	aluminum	2.5×10^{18}	1.3×10^{-18}	10.9	...
Fermilab	400	aluminum	6.6×10^{16}	5.0×10^{-17}	12.8	...
SLAC	18	iron	1.4×10^{19}	2.3×10^{-19}	2.5	1 to 3
ISR	11.5	stainless steel	3.5×10^{9}	1.1×10^{-9}	10.5	$\nu\geq1$
ISR	15	stainless steel	4.9×10^{9}	7.8×10^{-10}	14	...
ISR	22.5	stainless steel	4.2×10^{10}	9.0×10^{-11}	21.5	$\nu\geq2$
ISR	26.5	stainless steel	4.6×10^{10}	8.3×10^{-11}	25.5	...
ISR	31.4	stainless steel	4.6×10^{8}	8.3×10^{-9}	30.4	...

[a] Range of ν for which R_{max} in the table does not need any additional correction.

a milling machine advancing 10 μm between successive cuts.[14] Then, the chips were placed in a hollow rotating sphere to be randomized. They were divided into 30 samples and the magnetic charge of each sample was measured in an electromagnetic detector.[12,13]

THE MEASUREMENT OF THE MAGNETIC CHARGE

The detector is shown schematically in Fig. 1. The sample is carried several times around a path that traverses a coil (sensing coil). This coil is part of a superconducting circuit containing two other coils (field coils), each one wound around a sensitive magnetometer (SQUID).[15] If a sample has a nonzero magnetic charge, it will

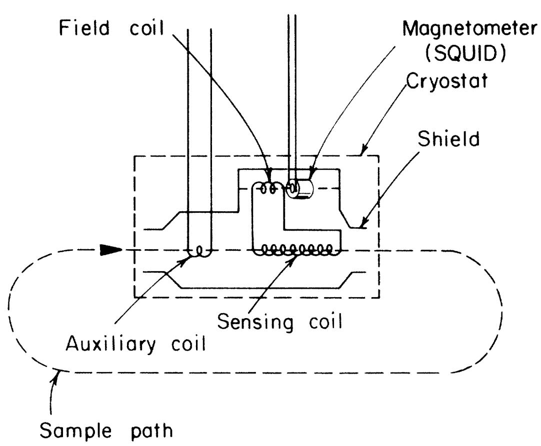

FIG. 1. Schematic view of the detector. The sample is moved along the dashed curve labeled sample path. The superconducting circuit is shown with the sensing coil and a field coil connected in series. The magnetometer and an auxiliary coil are also shown inside the cryostat.

induce a change of current in the superconducting circuit and a change $\Delta\phi_1$ and $\Delta\phi_2$ in the flux measured by SQUIDs 1 and 2. For each SQUID,

$$\frac{\Delta\phi}{\phi_0}=\frac{\nu_s N_p}{f}, \tag{1}$$

where ν_s is the ratio of the sample magnetic charge g_s to the Dirac unit

$$g_0=\frac{e}{2\alpha}\simeq\frac{137}{2}e \text{ (in Gaussian units)}, \tag{2}$$

ϕ_0 is the flux quantum of superconductivity (2.07×10^{-7} G cm^2), N_p is the number of passes through the sensing coil, and f is a constant, depending on the various inductances of the circuit.[13] For SQUID 1 (SQUID 2), $f=34$ (290).

The magnetic charge measurement was performed by taking magnetometer readings after 1, 3, 9, 27, and 81 passes. This procedure provided an accuracy of 0.03 on the value of ν_s, with the restriction described in Appendix A and in Ref. 13.

A magnetic charge is found to be zero if successive measurements of the current stored in the circuit are found to be the same within errors. Equipment instabilities would result in different current readings, i.e., in spurious nonzero magnetic charge measurement. In our procedure they would trigger a thorough check of the equipment and a remeasurement of the sample. Therefore, this method of search for monopoles is quite safe against equipment failures.

Furthermore, in the Maxwell equation,

$$\text{curl }\vec{E}=-\frac{1}{c}\frac{\partial\vec{B}}{\partial t}-\frac{4\pi}{c}\vec{J}_m, \tag{3}$$

the magnetic current $\vec{J}_m$ has the same effect as a time derivative of the magnetic induction $\vec{B}$.

Therefore, we were able to test the adequacy of our apparatus to detect magnetic charge using induction in the sensing coil, exactly as if magnetic charges were available for that test.

RESULTS

The magnetic charges ν_s of all the samples were measured consistent with zero and incompatible with any value larger than 0.1 (except for the restrictions of Appendix A). From this result, a maximum value R_{max} for the ratio of the number of monopole pairs to the number of interactions has been computed at a 95% confidence level. R_{max} is shown in Table II for the three different incident proton energies. These figures are valid when the monopole charge ν (in units of g_0) is included between 1 and 7, where the only sizable correction comes from the probability that chips of opposite charge end up in the same sample in spite of the randomization. For $1 \lesssim \nu \lesssim 7$, the expected energy loss of the monopole in aluminum[16]

$$\frac{dE}{dx} = \nu^2 \times 21 \text{ GeV/cm} \tag{4}$$

ensures that most monopoles stop in the targets and multiple scattering is large enough to separate the north and south poles of a pair by more than the chip size.

The upper limits σ_{max} for the cross sections for monopole pair production in proton-nucleon collision have been computed at a 95% confidence level and are plotted in Fig. 2. The interactions in aluminum were assumed to correspond to a total proton-nucleon cross section of 35 mb. Figure 2 shows σ_{max} for values of ν between 0.01 and 100, i.e., even for fractional values forbidden by the Dirac theory but for which our search is still meaningful. For $\nu > 7$ or $\nu < 1$, various corrections are needed, as described in Appendix B. In order to determine upper limits independent of the production process, the most unfavorable case for the monopole detection was considered, where monopoles of a pair are produced with a 0° opening angle and with the same energy. The upper limits indicated by the solid curve in Fig. 2 correspond to additional plausible assumptions concerning monopole properties,[17] the dashed curve corresponds to assumptions more favorable, and the dotted curve corresponds to assumptions extremely unfavorable for detecting monopoles. Assumptions for all three are described in Appendix B.

In any case, monopoles with masses larger than 12 GeV (that could not be produced in our proton-nucleon interactions), tachyons,[18] and zero-mass[19] monopoles (that would not stop in the material) would escape this search.

OTHER MATERIAL SEARCHED

The detector was also used to search for monopoles in a steel cylinder exposed to 18-GeV electrons at SLAC and in a $100\text{-cm}^2 \times 2$-mm-thick stainless steel piece of the ISR vacuum chamber that was located near an interaction point. No magnetic charge was found. The number of interactions seen by this material (including a correction for the solid angle in the ISR case) is shown in Table II. The value of R_{max}, the maximum ratio of the number of monopole pairs produced to this number of interactions, which is compatible with our results, is also shown.[20]

The SLAC target would have been suited to detect monopoles if their mass were lower than 2.5 GeV but their production cross section by electrons higher than by protons. The ISR material would be more suited if monopoles had a large mass, charge, and opening angle in the center-of-mass system. Unless one of these circumstances is true, the chance to detect monopoles here would be smaller than in cosmic-ray experiments.[8]

CONCLUSIONS

No monopoles were detected in material exposed to 4×10^{18} protons. The ratio of monopole pairs produced to the number of interactions is of the order of 10^{-18} or less for a large range of charge and for different assumptions about monopole properties. If monopoles have masses less than 12 GeV and are subject to strong interactions, pair production is affected by a very strong suppressing mechanism.[21] Indeed, hadrons, produced by strong interactions, are produced with cross sections that range from 10^{-27} to 10^{-30} cm^2, while weak interaction cross sections are of the order of of 10^{-36} cm^2 in this energy region. Our limits for monopole production cross sections by proton-nucleon interactions [Figs. 2(a) and 2(b)] are far below the figures for weak interactions. If monopoles exist, their masses are probably higher than 12 GeV.

Similar conclusions could be drawn from previous Fermilab experiments,[9,10] and their upper limits are only one or two orders of magnitude above ours. However, the validity of those earlier experiments is dependent on the assumption that a monopole can be extracted from material with or without a nucleus attached to it. Indeed, the extraction procedure cannot be tested without monopoles, while Eq. (3) shows that the effect of magnetic current used in our detector can be simulated exactly by magnetic induction. Some cosmic-ray experiments[4,5] also give cross-section limits only a few orders of magnitude above ours, but for them, assumptions about migration in the atmosphere and in the ocean water are needed in addition to the possibility of extraction. With respect to the cosmic-ray experiment using the lunar material,[6,8] the present experiment has the advantage of relying on more controlled conditions for the production and trapping of monopole pairs, and it results in limits about 3 orders of magnitude lower.

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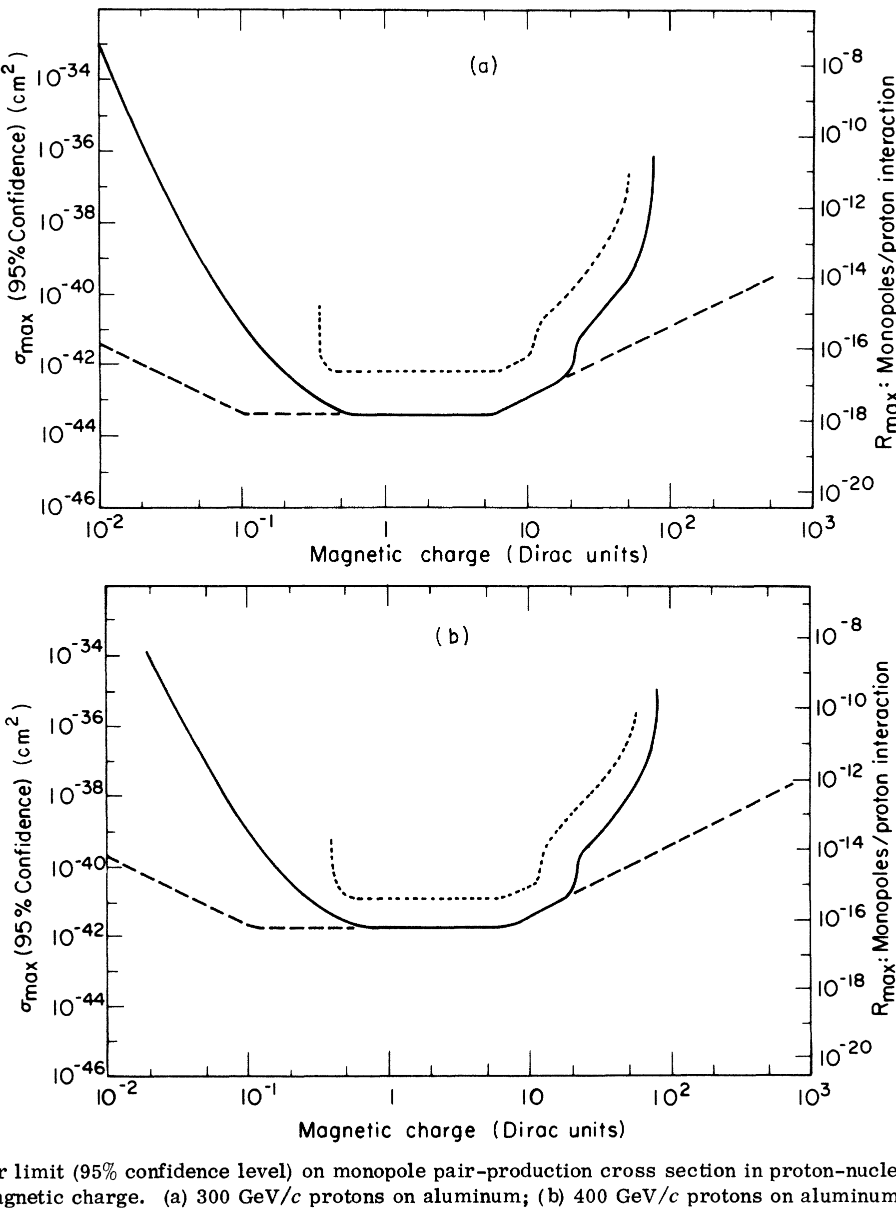

FIG. 2. Upper limit (95% confidence level) on monopole pair-production cross section in proton-nucleon collisions as a function of magnetic charge. (a) 300 GeV/c protons on aluminum; (b) 400 GeV/c protons on aluminum. The solid curve corresponds to corrections 1 to 4 described in Appendix B, the dashed curve to corrections 1 and 2 equal to 1. The dotted curve has been computed, using target 5 only, with a most pessimistic view of the sensitivity of the experiment.

possible only because the monopole detector was loaned to us by NASA.

APPENDIX A

Restrictions on the validity of our charge measurements for a few theoretically unexpected values of ν_s result from the periodic response of SQUIDs to magnetic flux changes.[13] After passing the sample N_p times, each SQUID provides a measurement of $\Delta\phi$, modulo ϕ_0, therefore of ν_s modulo f/N_p. Therefore, a measurement may fail to detect charges such that $\nu_s N_p/f_1$ and $\nu_s N_p/f_2$ are both equal to an integer within error. To avoid most of these failures, the search in the samples was performed with $N_p = 81$ with intermediate stops and magnetometer readings after $N_p = 1, 3, 9,$ and 27. Any magnetic charge would have been detected except for the small ones ($\nu_s < 0.1$) and some very special large ones (all $\geqslant 580$) equal within error, to a multiple of f_1 and f_2 at the same time.

APPENDIX B

For $\nu < 1$ and $\nu > 7$, the values of $R_{\max}$ given in Table II for the Fermilab targets need further corrections. Those corrections are highly charge-dependent and are deduced on the basis of assumptions described below.

For values of ν less than 1 (incompatible with the Dirac theory) the ionization is not sufficient to stop all the monopoles produced. A correction (referred to as correction No. 1 later on) is computed assuming all the monopoles are produced with a typical velocity equal to the velocity of the proton-nucleon center-of-mass system and that they lose $\frac{1}{2}$ of their energy every time they collide with an aluminum nucleus, as do protons at high energy when they collide with nuclei.[22]

North and south poles of a pair with large magnetic charges may stop close enough so that the attractive force between them drives them together toward annihilation.[23] Separation due to multiple Coulomb scattering is sufficient to avoid this effect for $\nu < 20$. For $20 < \nu < 60$, large-angle Coulomb scattering, and for $\nu > 60$, nuclear scattering with half energy loss are used to estimate a correction (No. 2). In all cases, we considered that monopoles of a pair are produced at the same energy and with a 0° opening angle.

Another correction (No. 3) takes into account the probability that the two monopoles of a pair end up in the same chip. It is estimated on the basis of multiple Coulomb scattering and affects the upper limits for $\nu > 7$.

If monopoles had charges $\nu < 0.1$, but there were many of them, the statistical fluctuations would generate some measurable charges for the samples. Therefore, our experiment allows computation of an upper limit for the density of such monopoles, with a reduced sensitivity (correction No. 4.)

These assumptions, which are quite pessimistic about the sensitivity of our experiment, correspond to the solid curve of Fig. 2. The dashed curve corresponds, for $\nu < 0.5$, to monopoles coming out of the aluminum nucleus in which they are produced with a very small energy (i.e., without correction No. 1), and, for $\nu > 20$, corresponds to magnetically charged aluminum nuclei very strongly bound to the crystal lattice (i.e., without correction No. 2). Therefore, the effect of correction No. 1 (No. 2) is shown by the difference between the solid and the dashed curves of Fig. 2 for $\nu < 1$ ($\nu > 7$). The effects of corrections Nos. 3 and 4 are shown by the difference between the dashed curve value for any selected ν and the solid curve value for $\nu = 1$.

In order to cover an even more pessimistic but unlikely case for the sensitivity of our experiment, wherein the magnetically charged aluminum nuclei do not bind to the crystal but would be free to move inside the material, a magnetized iron case producing a field of about 1.5 G was built around target No. 5. For a sufficient initial separation, the poles of a pair would drift in opposite directions along field lines to the iron, where they would be trapped.[24] The iron case was divided into separate samples and processed in the detector. The dotted line of Fig. 2 corresponds to that case and to the other pessimistic assumption where monopoles have no nuclear interaction (like muons), and do not stop in the target for $\nu < 0.5$.

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